The Operational Impact of QuikSCAT Winds at the NOAA Ocean Prediction Center

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Abstract

QuikSCAT has revolutionized the analysis and short-term forecasting of winds over the oceans at the NOAA Ocean Prediction Center (OPC). The success of QuikSCAT in OPC operations is due to the wide 1800 km swath width, large retrievable wind speed range (0 to in excess of 30 m s^{-1}), the ability to view QuikSCAT winds in a comprehensive form in operational workstations, and reliable near real-time delivery of data.

Prior to QuikSCAT, marine forecasters at the OPC made warning and forecast decisions over vast ocean areas based on a limited number of conventional observations or on the satellite presentation of a storm system. Today, QuikSCAT winds are a heavily used tool by OPC forecasters. Approximately ten percent of all short-term wind warning decisions by the OPC are based on QuikSCAT winds. When QuikSCAT is available, 50 to 68 percent of all weather features on OPC surface analyses are placed using QuikSCAT.

QuikSCAT is the first remote sensing instrument that can consistently distinguish extreme Hurricane Force conditions from less dangerous Storm Force conditions in extratropical cyclones. During each winter season (October through April) from 2001-04, 15 to 23 extratropical cyclones reached Hurricane Force intensity over both the North Atlantic and North Pacific Oceans. Due to QuikSCAT, OPC forecasters are now more likely to anticipate the onset of Hurricane Force conditions.

QuikSCAT has also revealed significant wind speed gradients in the vicinity of strong sea surface temperature (SST) differences near the Gulf Stream and shelf-break front of the western North Atlantic. These wind speed gradients are most likely due to changes in low-level stability

of the boundary layer across the SST gradients. OPC forecasters now use a variety of numerical guidance based tools to help predict boundary layer stability and the resultant near surface winds.

1. **Introduction**

The NOAA Ocean Prediction Center (OPC) is responsible for issuing marine wind warnings and forecasts of winds and seas for the extratropical High Seas and Offshore waters of the Atlantic and Pacific Oceans. OPC wind warnings and forecasts, in part, fulfill the United States requirement to provide marine warnings and forecasts under the 1974 International Convention for the Safety Of Life At Sea (SOLAS). Wind warning categories are based on the Beaufort Wind Speed Scale as described by Bowditch (2002), namely: Gale 34 to 47 kt (17.2 to 24.4 m s^{-1}), Storm 48 to 63 kt (24.5 to 32.6 m s^{-1}) and Hurricane Force 64 kt or greater (32.7 m s^{-1} or greater). In Bowditch (2002), winds speeds are given in whole knots whereas m s^{-1} are continuous and given to the nearest tenth. Since wind speeds are given in knots for all OPC graphical and text products, that convention will be maintained throughout this paper (conversion to m s^{-1} will follow in parentheses and may not exactly match the values above due to the rounding applied by Bowditch). OPC wind warnings are broadcast directly to mariners at sea and are used to make decisions regarding both safe and economic operations.

OPC forecasters issue these wind warnings for vast open ocean areas of the North Pacific and North Atlantic Oceans from the subtropics to the arctic. A variety of cyclone activity occurs across these waters including meteorological "bombs" during the fall and winter (Sanders and Gyakum 1980) and tropical cyclones undergoing extratropical transition during the summer and fall. Accurate and timely observations of meteorological conditions are necessary for OPC forecasters to make rapid and accurate warning decisions. Although conventional observations from buoys and Voluntary Observing Ships (VOS) are extremely useful to marine forecasters, their distribution is sparse and mostly limited to trade routes or continental waters.

Over the past twelve years, forecasters have come to rely more and more on remotely sensed data to help fill in the gaps inherent in conventional observations. OPC forecasters have used the winds derived from Special Sensor Microwave/Imager (SSM/I) available from the Defense Meteorological Satellite Program (DMSP) series of satellites. However, they are of limited value. SSM/I retrievals consist of wind speed only and not the full wind vector. The operational SSM/I winds available from NOAA NESDIS are processed using the retrieval algorithm developed by Goodberlet et al. (1989). These winds have an upper retrievable limit within the Gale warning category (less than 48 kt (24.5 m s^{-1})). Therefore, forecasters using SSM/I wind speeds can only distinguish between the lowest warning category and non-warning winds. Perhaps a larger hindrance is that SSM/I is not able to retrieve wind speeds in areas of liquid cloud and precipitation, which are of very high interest to marine forecasters as they often contain high winds (Atlas et al. 2001).

Scatterometer derived winds have been available to OPC forecasters for various periods over the last ten years. The European Space Agency's European Remote-Sensing Satellites (ERS) ERS-1 and ERS-2 winds were used by forecasters with minimal success as the swath width was narrow (500 km) and therefore the chances of retrieving wind vectors over a particular area of interest were small (Katsaros et al. 2001). In 1996, the NASA Scatterometer (NSCAT) was launched onboard Japan’s Advanced Earth Observing Satellite (ADEOS-I) and provided 90% coverage of the ocean areas within a two-day period. OPC forecasters used NSCAT data routinely and for the first time were able to view ocean vector winds over large ocean areas due to the two 600 km wide swaths. NSCAT also provided a wide range of retrieved wind speeds that extended well into the Storm Force category. For the first time forecasters were able to see retrieved winds over entire storm systems and differentiate between Gale and Storm Force winds

(Atlas et al. 2001). Unfortunately, the satellite suffered a catastrophic failure in July 1997. In 1999, in response to the loss of NSCAT, NASA launched the Quick Scatterometer Satellite with a SeaWinds scatterometer (henceforth referred to as QuikSCAT) onboard (Atlas et al. 2001). The QuikSCAT near real-time winds were accessible to OPC forecasters shortly after launch through Internet access. In October 2001, QuikSCAT winds were introduced to the OPC operational National Centers Advanced Weather Interactive Processing System (N-AWIPS) (desJardins et al. 1991) workstations and became fully integrated into OPC operations. In N-AWIPS, QuikSCAT winds can be displayed as an overlay or underlay and compared to observations, numerical model analysis and forecast fields, and conventional satellite imagery.

Several characteristics of QuikSCAT have made it a very popular tool for OPC forecasters. The data is available to the forecasters in near real time, on average within 90 minutes to 3 hours of data acquisition. The very wide 1800 km swath width provides ocean vector winds over 90% of the world oceans daily, and gives OPC forecasters two swaths for both the North Atlantic and North Pacific each day. QuikSCAT retrieves wind speeds to 58.3 kt (30 m s^{-1}) (near Hurricane Force) with an accuracy of ± 3.9 kt (2 m s^{-1}) (Shirtliffe 1999), although OPC forecasters have often observed QuikSCAT winds in excess of 63 kt (32.7 m s^{-1}) in association with extratropical cyclones (Von Ahn et al. 2004). Although QuikSCAT wind retrievals in areas of moderate to heavy rain can be contaminated this does not significantly detract from its use to forecasters in the extratropics.

In this paper we have attempted to quantify the impact of QuikSCAT winds on the OPC analysis and warning process. OPC operational QuikSCAT display capabilities will be discussed in Section 2. The results of several impact studies will be presented and discussed in Section 3. Section 4 addresses data concerns. The capability to detect Hurricane Force conditions will be discussed in Section 5. QuikSCAT winds have also revealed strong wind speed gradients across the oceanic thermal fronts of the western Atlantic. The impact on the forecasters' ability to see the sensitivity of near surface winds to the adjoining ocean surface temperature will be discussed in Section 6. Summary and conclusions will be given in Section 7.

2. OPC Operational QuikSCAT Display Capabilities

The operational forecast centers of the National Centers for Environmental Prediction (NCEP) use the N-AWIPS workstations to display observations, output from a variety of numerical models, and satellite imagery and data. N-AWIPS is also used to generate graphical analyses and forecast products. Each NCEP forecast center has tailored displays, capabilities, and functionality within the N-AWIPS designed for its specific mission and product suite. QuikSCAT winds first became available to OPC forecasters shortly after launch in 1999 via the Internet through the NESDIS Office of Research and Applications (ORA) webpage: http://manati.orbit.nesdis.noaa.gov/quikscat. While the Internet displays were useful to forecasters by allowing them to see the QuikSCAT winds, the data was viewed on a computer separate from the N-AWIPS workstations. There was no capability to overlay or underlay additional data sets with the QuikSCAT winds. When the QuikSCAT winds became available within the N-AWIPS workstations in 2001, this gave forecasters the ability to display and overlay a variety of fields using the same map background while in operational product generation mode. As an example, forecasters are able to overlay the most recent pass of winds from QuikSCAT with conventional satellite imagery while in the process of producing an analysis of surface features or preparing a High Seas or Offshore warning bulletin. Through their accessibility in the N-AWIPS environment, the QuikSCAT winds have become fully integrated into the OPC analysis and forecast process.

The QuikSCAT display capabilities are shown in Fig. 1. Display options have evolved since QuikSCAT was first added to the N-AWIPS workstations. Improvements to the display capabilities suggested by OPC forecasters are easily added during routine updates to the N-AWIPS. For example, the identification of the actual pass time for each swath was not initially displayed and QuikSCAT files were labeled by the time of completion of processing. Since several swaths can be displayed in one time period, the forecasters were not able to determine the age of an individual pass. To address this, the ability to display the exact time of each scan line was added to the QuikSCAT displays. Scan times can now be displayed in intervals as small as one minute using white lines with the time indicated at either edge of the swath as shown in Fig. 1.

Additional options for displaying wind speeds have also been added to N-AWIPS. Wind speed categories are color coded differently for rain-flagged data (color bar across the upper left side of the display) and non rain-flagged data (color bar across the upper right side of the display). The default color for rain-flagged winds is white. The default colors for non-flagged winds are coded to preset wind speed categories. Forecasters have the option to change the colors and the wind speed intervals to suit their individual preferences. The default white allows for easy identification of potentially rain-flagged winds. The latest version of N-AWIPS allows the forecaster to display the flagged winds using the color scheme for the non-flagged winds. This is extremely useful when the forecaster determines that an area of flagged winds is most likely not contaminated.

QuikSCAT display options continue to evolve within N-AWIPS. OPC forecasters now have both 25 km and 12.5 km resolution QuikSCAT winds available in N-AWIPS as shown in Fig 2.

The integration of QuikSCAT into the N-AWIPS display and product generation system has indeed contributed to the value of QuikSCAT winds to the OPC warning and forecast process. It is clear that flexible and tailored display capabilities coupled with timely and reliable delivery of data are keys to the success of QuikSCAT winds in the operational forecast environment.

QuikSCAT winds became available to NWS Weather Forecast Offices via the Advanced Weather Interactive Processing System (AWIPS) workstations with Office Build 3 (OB3) in the spring of 2004. NWS WFO's with coastal responsibility are now also able to view QuikSCAT winds when preparing coastal forecasts.

3. Impact On OPC Operations

Over the past two years, four studies were conducted to quantify the impact of QuikSCAT on OPC operations. The first three studies (fall 2002, spring 2003, and fall 2003) focused on the impact of QuikSCAT winds on the number of wind warnings issued for the North Pacific and North Atlantic Oceans. Wind warnings are displayed on the OPC oceanic surface pressure and frontal analyses completed four times a day at 0000, 0600, 1200, and 1800 UTC. Each of these three studies was conducted over a one-month period and was designed to have minimal impact on the forecasters' product preparation time. The final study (winter 2004) was expanded to examine the impact on ***all*** changes to the surface analyses, which included the placement of synoptic features such as front and pressure centers, and changes to the extent of warning and non-warning wind areas. This last study required significant forecaster input compared with the previous studies. Results from all four studies are shown in Table 1.

a. Studies 1,2,3

The wind warnings discussed for each of these studies refer to the short-term wind warning labels that are placed on the surface analyses that the OPC produces for the North Atlantic and North Pacific four times each day. These analyses are completed in real time and are transmitted to ships at sea at roughly three hours after synoptic time via United States Coast Guard High Frequency Radiofacsimile. They are also available via the Internet at http://www.opc.ncep.noaa.gov. Areas of high winds are labeled with the appropriate warning category on the surface analyses as shown in Fig. 3. For each study all warning labels (Gale or greater) that were placed on the surface analyses were logged in a spreadsheet. These were considered to be the number of warnings issued ***with*** QuikSCAT. Forecasters were also asked to fill out survey sheets after completing each surface analysis to list all warning areas, and to state what warning category would have been issued if QuikSCAT had ***not*** been available. These two data sets were compared and the difference represented the impact of QuikSCAT winds on the number of wind warnings issued by the OPC forecasters. This procedure was repeated for spring 2003 and fall 2003.

Results from the fall 2002 study, shown in Table 1, indicate that the number of wind warnings issued increased when QuikSCAT winds were included in the warning decision process. The impact was more significant in the Atlantic (30%) than in the Pacific (22%) and more importantly within the Storm and Hurricane Force warning categories (see Fig. 4).

The impacts for spring and fall 2003 were far less impressive than the first (Table 1.) In the North Atlantic and North Pacific, spring is a climatologically less active time of year than fall and winter. Thus the smaller impact in the spring 2003 study can be attributed to a lower number of significant wind events than the fall study. However, the fall 2003 period was no less active than the previous fall, so it was fully expected that the results of this study would be comparable with those of the first. Surprisingly, the survey of OPC forecasters showed far less impact than anticipated. The lack of impact brought up concerns that the QuikSCAT data was not being utilized to its full potential within the OPC.

A QuikSCAT usage survey was conducted to address these concerns. In querying the forecasters it became evident that they routinely disregarded *all* rain-flagged winds. This resulted in many good quality winds not being utilized. Prior to the fall 2003 study, lines that display the exact time the scatterometer data was acquired were added to the N-AWIPS workstation displays. Forecasters became more discriminate regarding the timeliness of data used in an analysis and were occasionally ignoring relatively recent data (6 hours old) over areas of ocean that were otherwise data void.

By routinely comparing QuikSCAT winds to numerical model analysis and forecast winds, OPC forecasters have gained confidence in numerical guidance winds and have begun to treat these winds as an equal "observation" to both ship and remotely sensed winds. This was an unexpected result of having improved observing capabilities and may indeed contribute heavily to the lower impacts of these last two studies. In other words QuikSCAT had no impact in determining the warning category unless the QuikSCAT winds were different from conventional observations ***and*** numerical model guidance winds. Prior to the winter 2004 study, forecasters were given a tutorial on the use of rain-flagged data and guidelines regarding the timeliness of data.

b. Study 4

The final study took place from 15 February to 15 March 2004. This study was conducted differently than the previous studies. Instead of only focusing on the number of wind warnings issued, additional questions regarding the use of QuikSCAT were asked of the forecasters including: changes to warning categories, changes to the areal extent of warnings, changes to wind speeds for a given area, and changes to the location of pressure systems and fronts. Forecasters were provided with a log for each surface analysis.

An “event” was defined as a wind warning area, a wind area less than warning category, a low pressure center, or a front. For each event the forecaster recorded the applicable information including: latitude, longitude, central pressure, warning category and whether or not QuikSCAT was available to use in the decision process. If QuikSCAT was used, the forecaster listed what change, if any, was made as a result of QuikSCAT winds. If no change was made this too was noted. This survey required significantly more of the forecasters’ time, but produced important diagnostic data.

At the end of the month long period the dataset was examined and events for which QuikSCAT were not available were removed. The remaining dataset was labeled events for which QuikSCAT was available. Examination of the second set of data revealed that QuikSCAT wind retrievals were available to use in the decision process 35% of the time in the Atlantic (173 events) and 63% of the time in the Pacific (294 events). This is a clear result of orbit times being asynchronous with synoptic analysis times. For example, the 0000 UTC and 1200 UTC Atlantic analyses typically have near full ocean coverage of QuikSCAT winds whereas the 0600 and 1800 UTC have no new data. Due to the large longitudinal extent of the North Pacific each Pacific analysis had at least one or two relatively recent QuikSCAT passes thus the higher usage percentage for the larger ocean. As shown in Fig. 5, during the times that QuikSCAT was available changes were made to more than half of the events (118 in the Atlantic and 146 in the Pacific). As in the previous studies the use of QuikSCAT resulted in an increase in the number of wind warnings issued for both oceans (10% for both the Atlantic and Pacific). Figure 6 gives a breakdown by the type of change (percentage) made to the surface analyses. Changes to wind speed and wind warning category accounted for more than half of the total in both oceans. Changes to the areal extent of specific wind fields made up more than 25% of the total. Surface features were changed the least (21% in the Atlantic, 12% in the Pacific). This may indeed be a testament to the quality of the overall numerical model analyses (which do ingest both QuikSCAT and SSM/I winds (Atlas et al. 2001)) that are used as a guess field for the surface analysis process. Given that QuikSCAT was only available twice daily for a specific area and the area of interest may have fallen within a data gap, this was a significant impact. Another SeaWinds scatterometer was launched onboard the ADEOS-II Satellite in December 2002. This would have provided increased coverage. Unfortunately the satellite failed in October 2003 and OPC forecasters were never able to utilize QuikSCAT and SeaWinds simultaneously.

The following examples illustrate how QuikSCAT was used to make changes to the surface analysis for two storm systems in the North Pacific. In the first example (shown in Fig. 7c) from 1200 UTC 27 April 2004, the forecaster analyzed a Gale with two low centers – 1000 hPa at 36°N, 151°W and 996 hPa at 33°N, 148°W. For the 1800 UTC analysis (Fig. 7d) in addition to the numerical model winds and ship observations the forecaster was able to look at both QuikSCAT and SSM/I passes over the area. The QuikSCAT pass for 1521 UTC (Fig. 7a) showed an area of non-rain-flagged Storm Force winds of 48 to 56 kt (25 to 29 ms^{-1}) in the southeast quadrant of the low. In this same area, an SSM/I pass (not shown) was not able to retrieve any wind speeds due to precipitation and liquid cloud contamination and only indicated a small area of Gale Force winds north of the low center. As seen in Fig. 7b, the 6-hour forecast of the NCEP Global Forecast System (GFS) indicated a single 1004 hPa low at 35°N, 150°W. The highest winds were a small area of near Gale Force winds 27 to 34 kt (14 to 17 m s^{-1}) located in the northwest quadrant. In the southeast quadrant of the low (where QuikSCAT revealed Storm Force winds), the GFS only showed speeds of 10 to 15 kt (5 to 8 m s^{-1}.) Based solely on the QuikSCAT pass, the forecaster analyzed the cyclone as a more intense single 988 hPa low with a much stronger pressure gradient and upgraded the warning category from Gale to Storm (Fig. 7d.) This first example illustrates how OPC forecasters use QuikSCAT winds with other data sets to improve surface analyses and short-term wind warnings. The forecaster chose QuikSCAT to upgrade a Gale warning to a Storm warning even though QuikSCAT was in disagreement with SSM/I winds and the short-term numerical forecast winds. The numerical model not only underestimated intensity but also the cyclone structure. QuikSCAT showed a strong inner core.

In the second example, shown in Fig. 8, from 1200 UTC 11 March, 2004 (Fig. 8c) an open wave 1007 hPa low was analyzed at 51°N, 162°W. GFS Model winds and ship observations indicated minimal Gale Force with only one ship reporting Gale Force winds (*ELZM* near 48ºN, 163ºW) to the south-southwest of the low (Fig. 8c). The forecaster placed a Gale warning label in the southeast quadrant of the low. At 1800 UTC the 6-hour forecast of the GFS continued to show a weak open wave without any closed isobars as shown in Fig. 8b. A single ship observation (*A8CN7,* 54ºN, 161ºW) north of the low showed an east wind of 15 kt (8 m s^{-1}) with a pressure of 1002 hPa (Fig.8d). Satellite imagery (Fig.8d) showed an impressive comma cloud formation suggesting a moderate to strong surface low center and supported the 1002 hPa ship observation. QuikSCAT from 1544 UTC (Fig. 8a) failed to show any easterly winds north of the center. However there is a small area of minimum QuikSCAT winds at 52ºN, 163ºW (to the southwest of the analyzed 1800 UTC low position) that may be indicative of a small low center at the QuikSCAT pass time of 1544 UTC. QuikSCAT did show a small area of non-rain-flagged

Storm Force winds in the southwest quadrant of the low surrounded by a larger area of Gale Force winds. Based on the QuikSCAT winds and the storm structure revealed in the satellite image the forecaster analyzed a 1000 hPa closed low and decided to upgrade the warning category to Storm Force on the 1800 UTC analysis (Fig. 8d). In this second example QuikSCAT showed an area of Storm Force winds but failed to close off a low center. This low was fairly small scale. A ship observation did indeed show an easterly wind. The forecaster chose to believe the Storm Force winds and upgraded the warning category accordingly. The inability of QuikSCAT to close off a low is quite evident with developing tropical cyclones and appears to be both a function of scale and reliance on an underlying numerical model initialization field in the ambiguity removal process (Edson et al. 2002). As in the first example, the forecaster used complimentary data (satellite imagery, ship observations and QuikSCAT) to make the best analysis and warning decision. In both examples if there had not been QuikSCAT data there would not have been a Storm warning.

4. Data Concerns

Precipitation is a significant source of contamination of QuikSCAT wind retrievals (Portabella and Stoffelen, 2001). Weissman et al. (2002) found that there are several reasons why this contamination occurs: attenuation of the radar signal, volume backscatter and roughening of the ocean surface. When it is raining, a portion of the transmitted energy is scattered back to the scatterometer and does not reach the ocean surface. This can result in an increase in the return energy measured by the scatterometer. Some of the transmitted energy is absorbed or scattered by the rain and is never measured by the satellite. Rain can also roughen the ocean surface changing the radar cross-section and resulting in an increase in return signal. The effect of rain on QuikSCAT wind retrievals is more pronounced for light winds than for the higher wind speeds (Portabella and Stoffelen, 2001). Stiles and Yueh (2002) found that for light winds (speeds less than 19 kt (10 m s^{-1})), QuikSCAT tends to overestimate the wind speed. As the wind speed increases this overestimation decreases as the signal from the surface increases. For winds greater than 29 kt (15 m s^{-1}) QuikSCAT wind speeds were underestimated. While errors of this magnitude are problematic for data assimilation schemes and numerical modelers, they do not pose a significant problem for OPC forecasters. Operational forecasters are more concerned with wind speed ranges rather than a specific wind speed value. The wind warning categories begin with wind speeds of 34 kt (17.5 m s^{-1})(Gale Force). This is well above the 10 m s^{-1} threshold described by Stiles and Yueh (2002).

. Hoffman and Leidner (2005) have shown that cross track wind vectors are often obtained under heavy rain conditions. Scattering from rain tends to be isotropic; there is no azimuthal modulation if rain dominates the signal. All backscatter values are the same as is the case for a cross-track wind. While cross track direction is an indicator of contaminated winds, this is not always the case. In the example below, the 12.5 km resolution QuikSCAT pass from 0800 UTC 04 November 2004 (Fig. 9a) reveals a large area of rain-flagged winds in the northeast quadrant of a low. Figure 9b shows the same QuikSCAT pass with the rain-flag turned off. A large area of easterly Gale Force winds is evident to the north of the low center. There is also a small area of easterly Storm Force winds embedded within the Gale area. On the surface analyses from 0600 UTC 04 November 2004 (Fig. 9c) it can be seen that the winds to the north of the low should, in fact, be easterly. In this case, although the winds are indeed cross track they are in agreement with the synoptic situation and were, therefore, accepted.

In regions of scattered convection such as the subtropics or tropics, rain contamination is problematic. An example of scattered tropical convection is shown in Fig. 10. The area of concern is in the tropical North Atlantic on 01 December 2004. The Lesser Antilles can be seen on the extreme western portion of the images. The 25 km resolution QuikSCAT winds for 0934 UTC as displayed on the N-AWIPS workstations are shown in Fig. 10a (rain contaminated winds in white) and Fig. 10b (rain contamination flag turned off). Looking at the rain free areas in Figs. 10a and b, one can see that the underlying flow is from the northeast 15 to 20 kt (7.7 to 10 m s^{-1}) to the northwest of the convection with weaker winds to the east at 10 to 15 kt (5 to 7.7 m s^{-1}.) However, rain-flagged winds in Fig. 10a range from 20 to 45 kt (10 to 23 m s^{-1}), which is significantly higher than the underlying northeast trades. Wind directions are, for the most part, northeast and cross track (parallel to the timeline) but do show considerable variability. This is an area where forecasters would have little confidence in the retrieved wind speeds and directions.

This example illustrates the difficulty using QuikSCAT winds without a concurrent measure of rain rate to help determine the validity of wind speeds in areas of scattered convection in the tropics. What should a forecaster do? It is suggested to look at the overall rain free flow to establish a baseline, and then examine the higher winds along the periphery of the convection to see if there is an overall distribution of about 20 to 25 kt (10 to 12.9 m s^{-1}) in this case. Also, examine any conventional observations that might help to support stronger winds. In this example the authors would be hesitant to accept winds in excess of 30 kt (15.4 m s^{-1}) as ground truth. To mitigate the problem described here, it is crucial that future scatterometers have an independent concurrent measure of rain rate.

Although wind retrievals in areas of moderate to heavy rain may indeed be contaminated, forecasters still find the scatterometer winds to be very useful when making warning decisions. The Multidimensional Histogram (MUDH) rain-flag (Huddleston and Stiles 2000) that is used to indicate possible rain contamination is overly conservative with too many false alarms especially at high wind speeds (Hoffman et al. 2004.) Since no direct measurement of rain is possible with QuikSCAT the MUDH algorithm uses a probability of contamination index. Not all the data that is rain-flagged is contaminated and to outright reject all flagged data results in the loss of many useful observations (Yu and Gemmill 2004). Thus, it is imperative that forecasters understand how to interpret flagged data.

5. Hurricane Force Extratropical Cyclones

Hurricane Force (referred to as HF) extratropical cyclones are a significant threat to safety at sea. Dangerous winds and waves associated with these extreme cyclones can cover vast ocean areas and result in the loss of lives and property. The economic impact is far reaching and can consist of loss or damage to cargo or a vessel, increased transit times, increased fuel usage, lost time due to vessel damage, and late delivery of perishable goods. Prior to QuikSCAT, there was no data source available to ocean forecasters that consistently observed HF winds in extratropical cyclones. Merchant ships do occasionally report extreme conditions but not routinely enough for forecasters to be able to consistently differentiate the extreme HF cyclone from the more common Storm Force cyclone. QuikSCAT has given OPC forecasters this consistency.

The ability of QuikSCAT to detect winds in excess of minimal HF has resulted in an increase in the number of advanced warnings for HF conditions by OPC forecasters (Von Ahn et al. 2004). The number of HF events observed (based on 25 km QuikSCAT winds and conventional ship observations) over the past three winter seasons for the North Atlantic and Pacific is shown in Table 2. For each period of study 15 to 23 HF events occurred in each ocean basin. The Pacific exhibited maximum activity in November and December with a reduction in activity in January. The Atlantic consistently had a maximum number of events in January. Peak activity occurs over the western portion of each ocean basin in agreement with the "meteorological bomb" work by Sanders and Gyakum (1980). Both ocean basins appear to have preferred tracks for these extreme cyclones. HF conditions on average appear to be short-lived (less than 24 hours) making the forecast problem more difficult. Verification of OPC 48 and 96 hour forecasts of cyclone intensity, location, and warning category for October 2003 through March 2004 have shown that these extreme cyclones are very difficult to forecast at the day 4 forecast projection (Sienkiewicz et al. 2004), particularly over the North Pacific.

Composites of maximum winds observed by QuikSCAT for open ocean HF cyclones from October 2003 to March 2004 (11 in the North Pacific and 6 in the North Atlantic) are shown in Fig. 11 a and b. The center point of the composites is the location of the attending low pressure system, thus making the composites cyclone-relative. In each composite the direction north is up and east is to the right. A distance scale of 300 n mi can be found at the lower left of each figure as a reference. These composites were created as a guide to help forecasters anticipate the preferred location of maximum winds relative to the storm center. Both composites show a large area of HF winds to the south of the cyclone center in a crescent shape. Browning (2004) in a detailed wind field analysis of the Great Storm of 1987 showed that the highest observed winds were also found in a crescent shaped area to the right of the cyclone track outward of the occluded or bent back front and in the dry slot of the cyclone. Browning referred to this as the sting at the end of the tail where the tail is the tip of the cloud head. This area of the mature cyclone is on the cold side of the surface occluded or bent back front as described by Shapiro and Keyser (1990) and often contains very strong cold air advection along with a deepening well-mixed boundary layer.

Prior to the availability of QuikSCAT OPC forecasters were not able to routinely detect winds of HF intensity within extratropical cyclones. Before QuikSCAT, the intensities of many storms were likely underestimated with warnings one category too low (Storm versus HF). Given that these extreme conditions are short-lived it is of great importance that the areas of HF winds are accurately identified and warned for in a timely manner.

The following case is an example of how OPC forecasters used QuikSCAT to detect and warn for short-lived HF conditions. The HF extratropical cyclone in this example began as a 1015 hPa low in southwest Minnesota on 1800 UTC 08 March 2004. The low moved southeastward and emerged into the Atlantic off the Georgia coast. At 0600 UTC 09 March, the low was analyzed at 32°N, 76°W as a 1011 hPa Gale with a Developing Storm Force wind warning. As the low moved northeasterly across the waters of the Gulf Stream it began to intensify. At 1200 UTC 10 March (Fig. 12a) ships were reporting winds in 25 to 30 kt (12.8 to 15 m s^{-1} range (near Gale Force). The 1059 UTC QuikSCAT pass (Fig. 12b) showed an area of 56 to 63 kt (28.8 to 32 m s^{-1}) winds (Storm Force). Based on this pass the forecaster analyzed higher winds on his 1200 UTC surface analysis and upgraded the cyclone to Storm Force. Because he anticipated further strengthening he raised the warning category to Developing HF (Fig. 12a) giving mariners notice prior to extreme conditions occurring. This deepening trend continued through 1800 UTC. The 2317 UTC QuikSCAT pass (Fig. 12d) showed an area of non rain-flagged HF winds of 70 kt (36 m s^{-1}) to the north of the low center with a broad area of Storm Force winds to the north and west. As seen in Fig. 12c a ship observation (*KRHX*, 37ºN, 73ºW) of 50 kt (26 m s^{-1}) (depicted by a red wind barb) was found in this area confirming the QuikSCAT Storm Force winds. Based on the QuikSCAT HF winds, the forecaster upgraded his warning category to HF on the 0000 UTC 11 March surface analysis. There is no doubt that without QuikSCAT the forecaster would not have increased his warning above Storm Force. The cyclone was still intensifying at 0600 UTC with a drop of 9 hPa from the previous analysis. Based solely on available ship observations, (there was no new QuikSCAT data available), the cyclone was downgraded to a Storm on the 0600 UTC 11 March surface analysis. At 1200 UTC intensification had slowed considerably with a drop of only 1 hPa. Several ships reported wind speeds of 54 to 60 kt (28 to 31m s^{-1})(still close to HF). The 1039 UTC QuikSCAT pass showed maximum wind speeds of 54 kt (28 m s^{-1}) (Storm Force). All observations supported the forecaster's decision to maintain the Storm Force warning. During the intensification of this storm QuikSCAT consistently showed winds to be stronger than the ship observations and the model forecasts. One could assume that this would have been true at 0600 UTC. Considering that the cyclone rapidly intensified between 0000 UTC and 0600 UTC and that ship observations at 1200 UTC (6 hours later) were still so close to HF it is conceivable that the HF conditions may have still been present at 0600 UTC. This case is a prime example of how QuikSCAT winds have given forecasters the ability to identify these hazardous short-lived extreme conditions. In this instance the forecaster was able to confirm the accuracy of the QuikSCAT winds and anticipate further strengthening. Without QuikSCAT winds the warning for this cyclone would have remained at the Storm Force category. QuikSCAT has indeed raised forecasters awareness concerning these high impact intense ocean storms.

6. Gulf Stream Applications of QuikSCAT winds

The OPC Atlantic Offshore zones extend from roughly 46 to 460 km off the United States East Coast and include the complex sea surface temperature (SST) gradients of the Gulf Stream, slope and shelf waters. In a case of southerly low-level flow (from the warm Gulf Stream across the cooler shelf waters), Sweet et al. (1981) observed from aircraft a nearly 50% reduction in near surface wind speed across the Gulf Stream north wall. Near calm conditions were observed over the cooler slope and shelf waters with rougher seas and higher winds over the Gulf Stream. The differences in wind speed and sea state across the Gulf Stream north wall were attributed to differences in boundary layer stability. It was surmised that calm seas and surface winds north of the Gulf Stream were due to stabilizing effects of the cool SST's. Low static stability over the warmer Gulf Stream waters was thought to account for enhanced mixing, stronger winds and increased sea state. In an observational study of the Eastern Tropical Pacific Ocean using QuikSCAT winds, Chelton et al. (2001) found that SST structures are reflected in the wind stress field. Surface wind stress was reduced by a factor of four over the cold equatorial tongue and increased by nearly the same amount again over the warmer water to the north. It was surmised that this reduction in wind stress was due to a decoupling of the surface winds from winds aloft due to a stabilizing of the atmospheric boundary layer. Wallace et al. (1989) earlier had proposed that the surface winds respond to the modification of the boundary layer stability by the underlying SST.

Using a mesoscale numerical model, Desjardin et al. (1998) studied the potential impact of Gulf Stream meanders and cold and warm rings on the marine atmospheric boundary layer (MABL) during the Superstorm of March 1993. Their simulations using a high resolution SST showed that the wind speed pattern in the southerly surface flow in advance of the strong cold front matched the Gulf Stream SST features. Stronger winds were found over warm water features and weaker winds over the cooler SST features. An unstable well-mixed MABL was present over the Gulf Stream meanders and warm rings allowing for increased vertical momentum transfer and enhanced wind speeds. Statically stable conditions and minimized vertical momentum transfer occurred over the colder waters resulting in lower wind speeds.

The all weather capability of QuikSCAT has helped to reveal significant near surface wind gradients across the SST gradients or fronts of the Gulf Stream. At 1200 UTC 21 March 2003 a long southerly fetch of winds extended from the Bahamas to New England. Shown in Fig. 13 is a 3-day SST composite from GOES satellite data for 21 March 2003 (13a) and QuikSCAT scatterometer derived winds (13b). The North Wall of the Gulf Stream is shown by a solid white line in Fig.13a and 13b. Gale Force winds of 34 to 43 kt (17.5 to 22 m s^{-1}) were observed over the Gulf Stream core. To the north of the Gulf Stream QuikSCAT observed southerly winds of 15 to 20 kt (7.5 to 10 m s^{-1}). This was less than half the wind speed over the Gulf Stream itself. Similar to the modeling study of Desjardin et al. (1998), the shape of the wind maximum closely follows the contours of the Gulf Stream North Wall (shown by a solid white line). Numerical weather prediction model forecast guidance used by OPC forecasters typically does not forecast gradients of the low-level wind speed as shown in this example.

It should be mentioned that the scatterometer infers a wind speed from the surface roughness. That wind speed is an equivalent neutral wind (Tang and Liu 1996) adjusted to a height of 10 m. In this example it is assumed a very strong shallow inversion exists over the cooler SST's. The height of this strong inversion is not known. Over the cooler waters an equivalent neutral wind would represent an underestimate of the actual wind speed at 10 m. The opposite is true for the unstable boundary layer over the warmer waters (although this effect decreases with increased wind speed and may be minimal at the wind speeds here). Ideally, the OPC forecasts winds at a height of 10 m. However, given the lack of sea truth and the fact that the equivalent neutral wind is more closely related to the wind stress and the ability of the wind to generate waves (of concern to the mariner) it is believed that the difference is not that significant in cases such as those presented here.

Examples from QuikSCAT have raised the awareness of OPC forecasters to the significance of low-level stability on near surface wind speed. OPC forecasters now use a variety of numerical model based tools and fields to estimate the near surface stability and wind. These include: FM 94-IX Binary Universal Form for the Representation of Meteorological data (BUFR) soundings from the NCEP Eta model (Black 1994), shallow surface based lifted indices such as surface to 975 hPa level, the difference between numerical model surface temperature and first sigma level temperature from the NCEP GFS model (Kanamitsu 1991), and height of the boundary layer and maximum wind gust from the NCEP Eta using a technique developed by Benjamin et al. (2002). Of the guidance available to forecasters, the BUFR model soundings and height of the MABL have been particularly useful. OPC's Ocean Application Branch (OAB) is developing a technique to correct numerical model near surface wind speeds to values observed by QuikSCAT by applying a bias correction. This bias correction is based on the difference between numerical model forecast wind speeds and inferred QuikSCAT wind speeds in a variety of low-level stability profiles. The goal of this effort is to provide improved wind guidance to the forecasters and improve wind forecasts over the complex SST fields found in the Atlantic Offshore waters.

7. Conclusions

In this paper we have attempted to quantify the impact of QuikSCAT winds on OPC operations. The initial surveys of the forecast staff focused on the short-term marine warning categories displayed on oceanic surface pressure and frontal analyses. The first survey revealed a significant increase in marine warnings due to the use of QuikSCAT data; 30% (Atlantic) and 22% (Pacific) of wind warnings were attributed to QuikSCAT. Two subsequent studies showed far less impact (on average 5% increase for both oceans) on the number of warnings. The period of the initial study was the first time that QuikSCAT was used consistently by all of the forecasters. An initial enthusiasm due to the introduction of QuikSCAT to some forecasters may have been reflected in the increased number of warnings.

The decrease in impact in the two follow-on studies can be attributed to several factors. In the follow-on studies, timelines displaying data acquisition times were introduced to the operational N-AWIPS workstation displays. This resulted in the forecasters becoming more discriminating regarding the age of QuikSCAT data used. Not all forecasters had been using the same cut off times for using the QuikSCAT winds. Additionally, forecasters did not fully understand the rain-flagging and were thus discarding useful data. This issue was addressed through increased training. Lastly, a surprising result was that OPC forecasters had gained a significant confidence in the quality of the numerical guidance winds from the GFS because of QuikSCAT. This confidence stems from the everyday comparison of GFS short-term forecasts and QuikSCAT winds. When determining the warning category for an area of high winds, OPC forecasters apparently treat the GFS guidance winds with nearly as much weight as the observed or remotely sensed winds. When the QuikSCAT winds supported model winds forecasters consistently did not record this as a positive impact of QuikSCAT.

While the first three studies focused solely on the number of warning decisions made, the last study perhaps best illustrates the positive impact of QuikSCAT winds on OPC operations. When available, QuikSCAT winds were used to locate surface features and to identify the intensity and the extent of wind areas on OPC surface analyses 68% (Atlantic) and 50% (Pacific) of the time. This is particularly impressive in the Atlantic where timely QuikSCAT data was only available 35% of the time (a function of orbit timing versus synoptic hour). The last study also showed that 10% (both Atlantic and Pacific) of warning categories were solely determined using QuikSCAT winds.

Precipitation contamination continues to be a problem when interpreting QuikSCAT winds. This appears to be a particular problem in areas of convection in the tropics and subtropics. There are times when forecasters do not have enough information to either believe or disregard QuikSCAT winds. It is crucial that future wind retrieval instruments have concurrent wind and rain rate measurements.

In December of 2000, the U.S. National Weather Service began issuing HF wind warnings for winds 64 kt (32.9 m s^{-1}) or greater in association with extratropical cyclones. Prior to December 2000, the NWS only used the word hurricane for Atlantic and eastern Pacific *tropical* cyclones. Two wind warning categories were used: Gale - 34 to 47 kt (17.5 to 24.2 m s^{-1}) and Storm - 48 kt and higher (24.3 m s^{-1} and greater). Under the two warning category system, there was no way to distinguish between a minimal 50 kt (25 m s^{-1}) Storm and a rare 75 kt (38 m s^{-1}) extreme winter cyclone. Storm warnings were issued for both types of cyclones. Until QuikSCAT, no observing system was able to consistently observe or infer winds 64 kt or higher (32.9 m s^{-1}) over the open ocean. QuikSCAT's wide swath, all weather capability and high wind speed retrieval range has given forecasters the ability to observe and the confidence to forecast these most severe cyclones. Over the months from October 2001 through March 2004 OPC forecasters have issued HF warnings for 120 different extratropical cyclones over the North Atlantic and Pacific basins. QuikSCAT's ability to detect Hurricane Force conditions has become a critical capability for the operational forecasters of the OPC. This capability is a paramount requirement for future satellite based ocean wind retrieval instruments.

Forecasting near surface winds over the highly dynamic waters of the Gulf Stream in the western North Atlantic continues to be a challenge. QuikSCAT has observed strong wind gradients in the vicinity of SST fronts, where these gradients are attributed to large differences in boundary layer stratification. Forecasters now routinely use a variety of numerical model based parameters and tools such as: low-level lifted indices, height of the boundary layer, winds from a variety of low levels, and detailed numerical model soundings to forecast near surface winds. QuikSCAT has helped forecasters to better understand the relationship between low-level stability, SST, and near surface winds. This relationship revealed by QuikSCAT illustrates the need for accurate and timely high-resolution SST analyses in order to improve forecasts of near surface winds.

QuikSCAT winds have certainly made a very positive impact on OPC operations. This positive impact is due to the reliability of the data, timeliness of delivery, the large swath width, the large retrievable wind speed range, and the ability to view the data in operational workstations in a comprehensive form. Although rain is a problem it is not an insurmountable problem in the extratropics. The ability to distinguish between Storm and HF winds has revolutionized the short-term oceanic wind warning process at the OPC.

Even though QuikSCAT has become a heavily used tool by OPC forecasters, there is still more to be gained from QuikSCAT winds in operations. Much of the discussion in this paper focused on the use of QuikSCAT derived wind speed only. Future work at the OPC will focus on using the full wind vector by implementing the University of Washington Planetary Boundary Layer (PBL) Model (Patoux et al. 2003) to retrieve sea-level pressure (SLP), divergence, and surface vorticity in real time from QuikSCAT winds. These fields will be used as guidance by forecasters to more accurately estimate the central pressure, pressure gradient, and frontal structure of extratropical cyclones.

The impacts described in this paper are impressive even though forecasters only see two vector wind snapshots of a given ocean each day from QuikSCAT. It was hoped that the SeaWinds scatterometer onboard ADEOS-II would give forecasters more than 12-hour snapshots and allow them to better see the evolution of wind and weather systems. However, ADEOS-II failed before SeaWinds data could be integrated into OPC operations. We intend to evaluate the potential impact of dual scatterometers on OPC operations using the data recovered from the six-month overlap period between QuikSCAT and SeaWinds.

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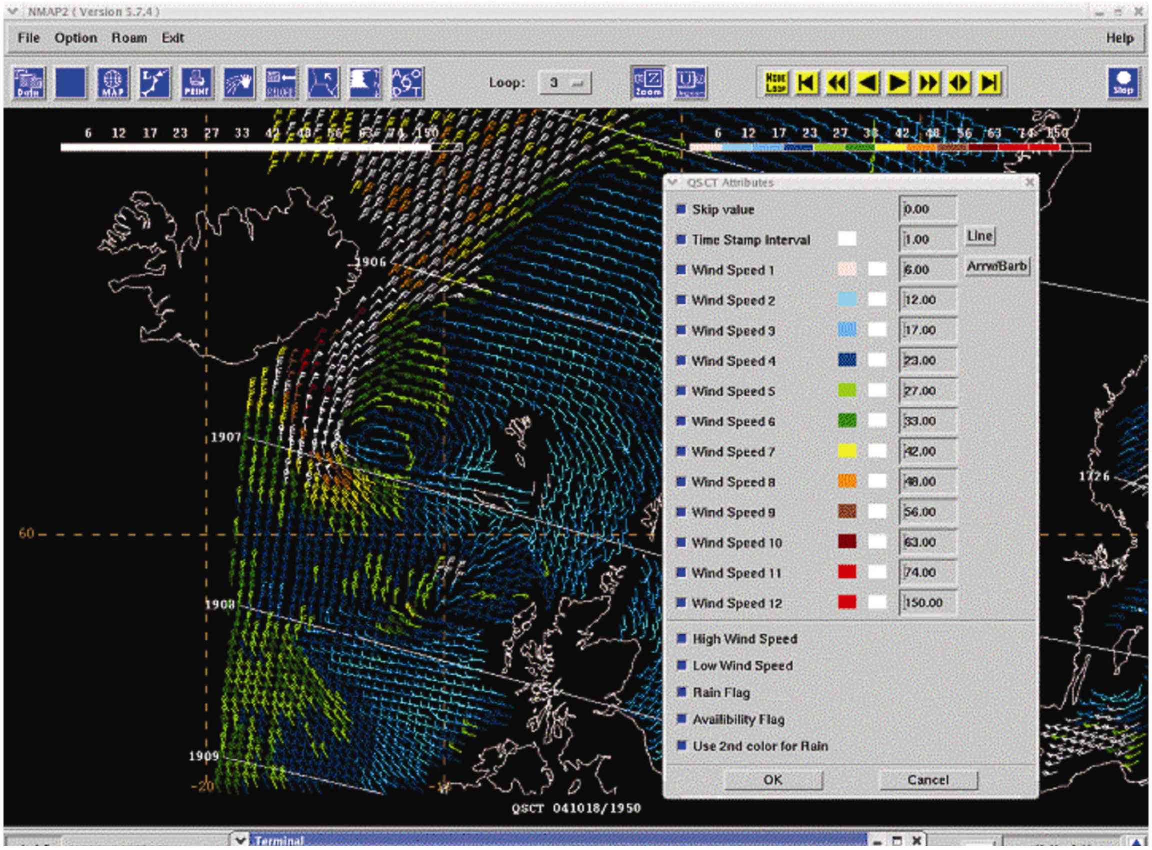

Fig. 1: Screen capture of N-AWIPS workstation display of QuikSCAT winds. Wind vectors are plotted as conventional wind barbs in knots. Rain-flagged winds are depicted in white (color bar in upper left); non rain-flagged winds are depicted in colors according to preset wind speed categories (color bar in upper right). White lines with time stamp (in one minute intervals) at each end of the swath indicate the time (UTC) of data acquisition. These attributes can all be edited from within the QSCT attribute window (right side of figure).

a b

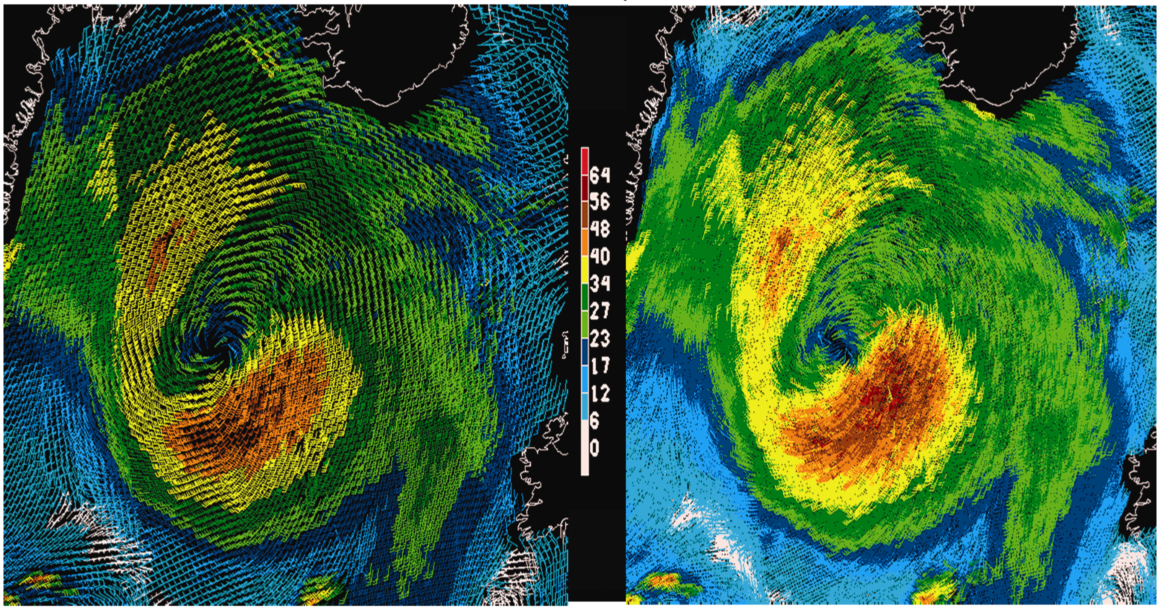

Fig. 2: QuikSCAT winds as in Fig.1 from 0709 UTC 07 October 2003 of a North Atlantic cyclone with rain-flag turned off showing (a) 25 km resolution and (b) 12.5 km resolution.

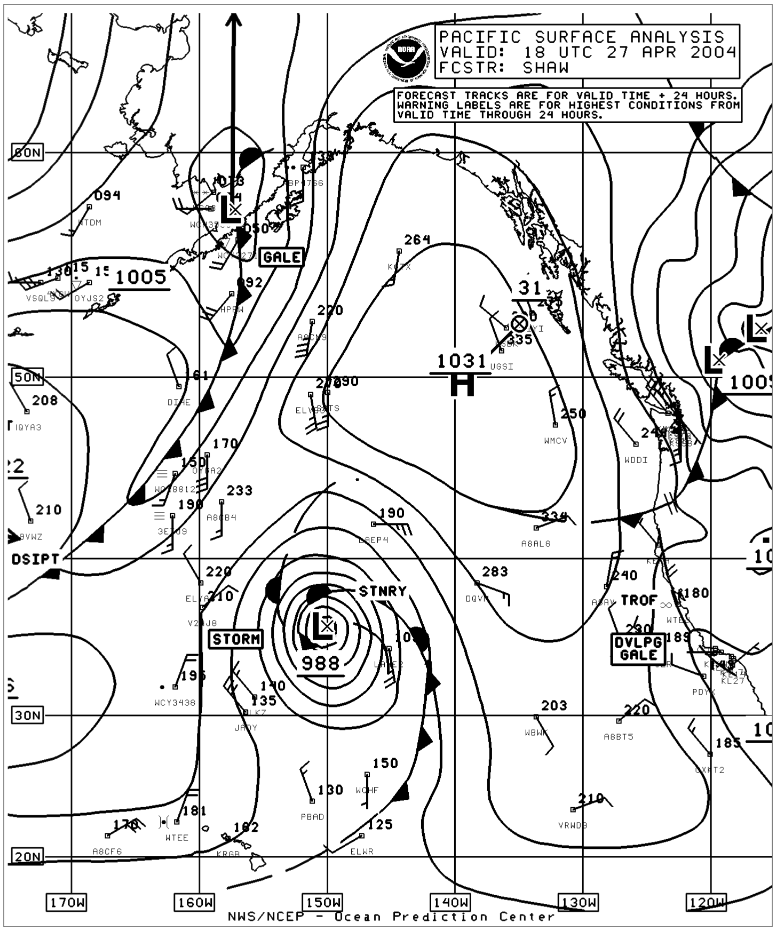

Fig. 3: Example of OPC Surface Analysis from 1800 UTC 27 April 2004. Surface features (high and low pressure centers, fronts, and troughs) are depicted using conventional symbols. Surface pressure is drawn with black isobars in 4 hPa contour intervals. Surface observations are plotted using a truncated station model showing wind speed and direction, sea level pressure and observing ship radio call sign. Winds are plotted in barbs in knots. Wind warning categories are denoted as text boxes placed in the appropriate location. Black arrows show the 24-hour forecast track; a black x is used to show the 24-hour forecast position for low pressure systems.

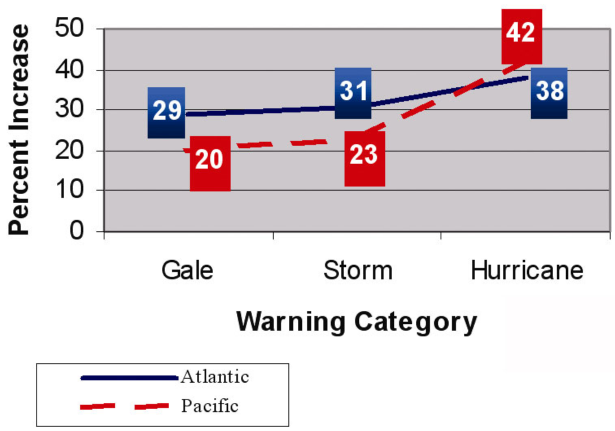

Fig.4: Percent increase in the number of wind warning labels placed on OPC surface analyses (from 15 November to 15 December 2002) as a function of warning type. Atlantic results are shown as a solid blue line and Pacific results as a dashed red line.

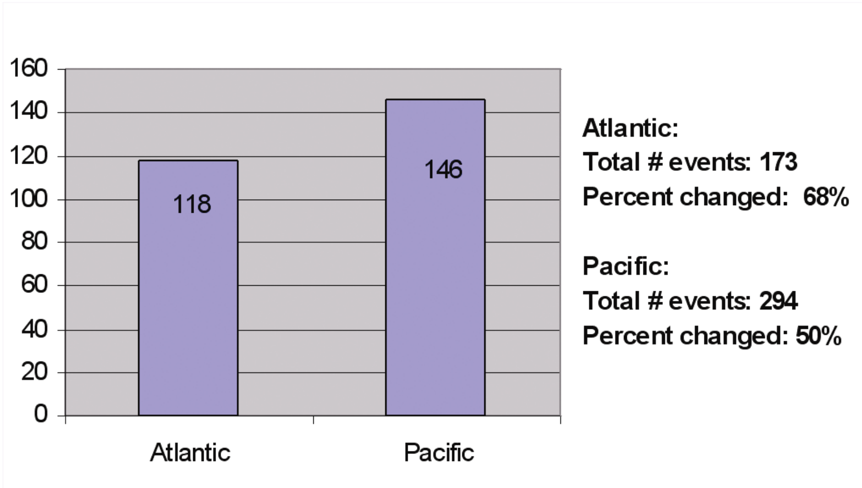

Fig. 5: Number of events changed on OPC surface analyses using QuikSCAT winds for the North Atlantic and the North Pacific during the period from 14 February to 15 March 2004.

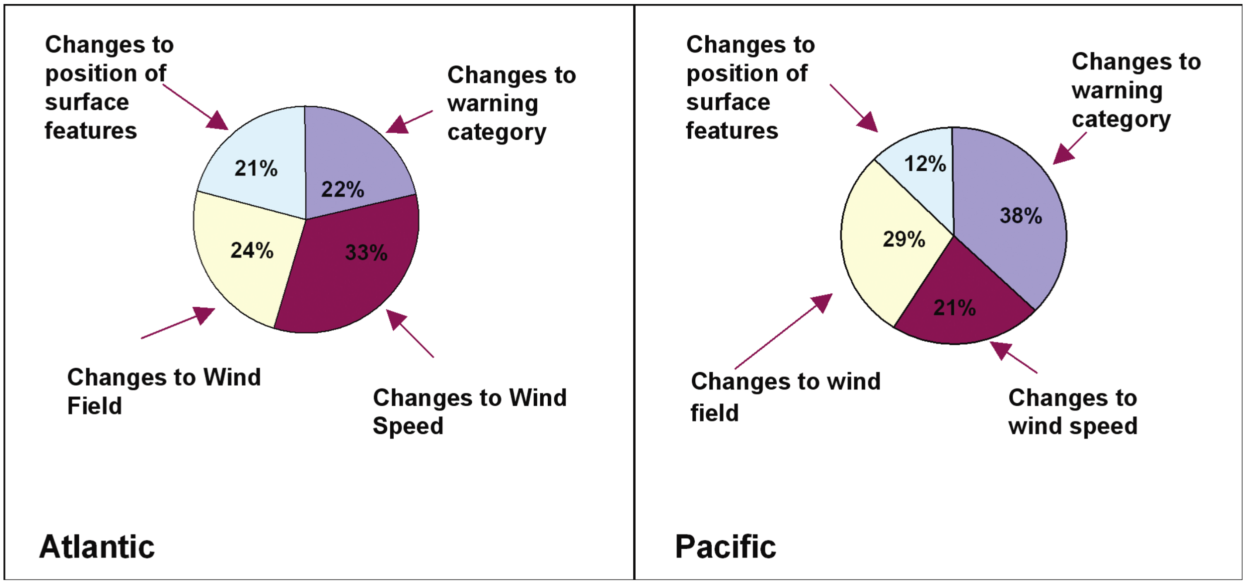

Fig. 6: Percentage of changes made to OPC surface analyses when QuikSCAT was available for the North Atlantic and the North Pacific from 14 February to 15 March 2004.

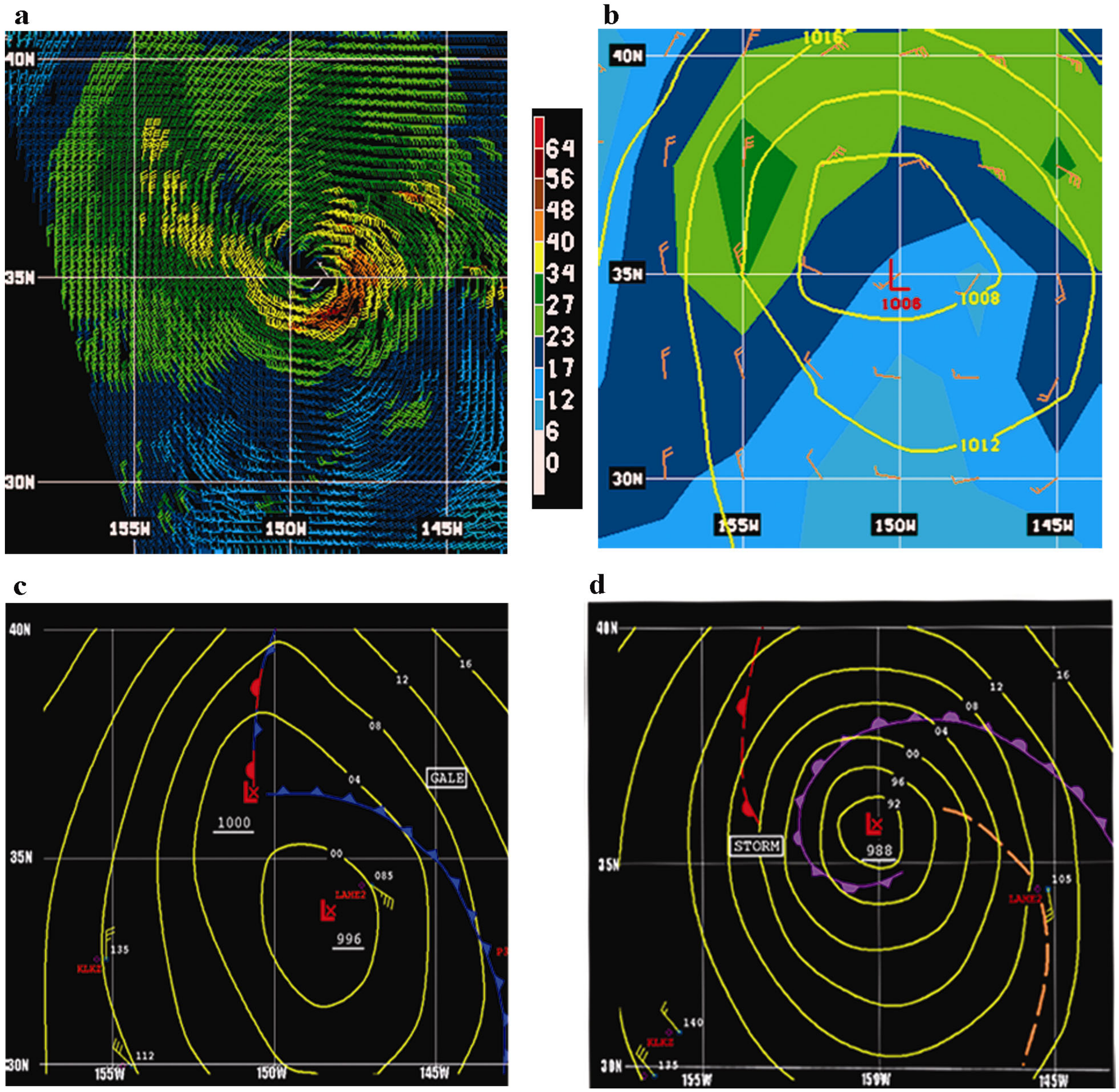

Fig. 7: Four panel from 27 April 2004 for the North Pacific for an area centered at 35ºN, 150ºW showing (a) QuikSCAT winds for 1521 UTC 27 April 2004. Winds are plotted in knots with color-coded barbs (color bar in center panel). An area of Storm Force winds (brown and burgundy wind barbs) is located to the southeast of the low center. (b) The 6-hour forecast of the NCEP GFS model valid 1800 UTC 27 April 2004. Isobars are drawn in yellow in 4 hPa contour intervals. Surface wind vectors are plotted as conventional wind barbs. Wind speed categories are shown by color-shading using the same color scale as QuikSCAT in (a) (color bar in center panel.) (c) Screen capture of OPC surface analysis for 1200 UTC 27 April 2004. Isobars are drawn in yellow in 4 hPa intervals. Low pressure centers indicated by a red Lx. Fronts are depicted with standard symbols. Ship observations plotted with a truncated station model as in Fig. 3. Winds are plotted in barbs in knots. Wind warning areas depicted with a text box in the appropriate location. (d) Same as (c) except for 1800 UTC 27 April 2004.

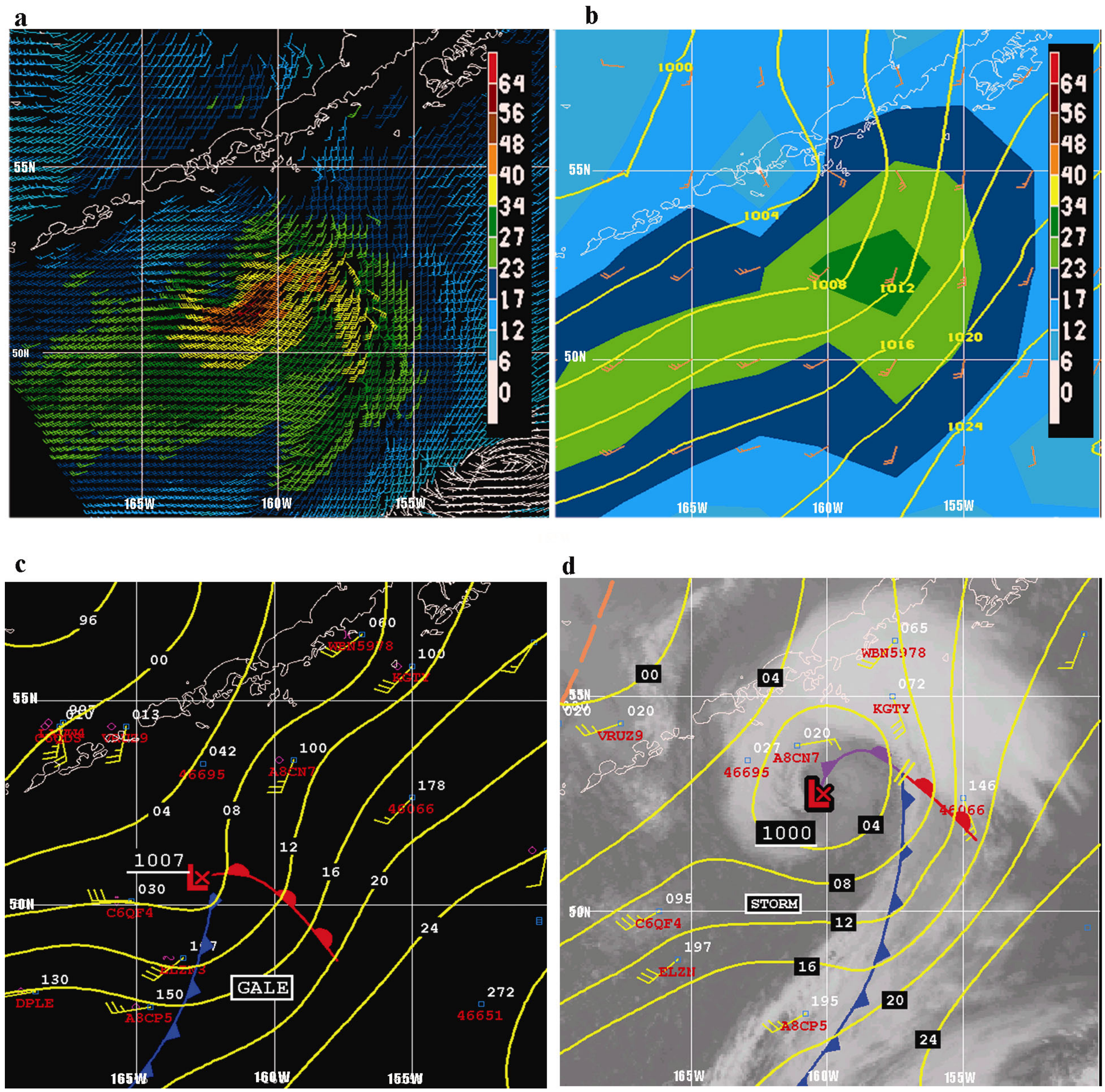

Figure 8: Same as Fig. 7 for 11 March 2004 for an area centered at 52ºN, 160ºW showing (a) QuikSCAT winds for 1544 UTC 11 March 2003 (color bar in right side of image), (b) NCEP GFS 6 hour forecast of sea level pressure and wind speed (color bar in right side of image) for 1800 UTC 11 March 2004 (c) 1200 UTC 11 March 2004 OPC Surface analysis and d) 1800 UTC 11 March OPC analysis and GOES IR satellite image.

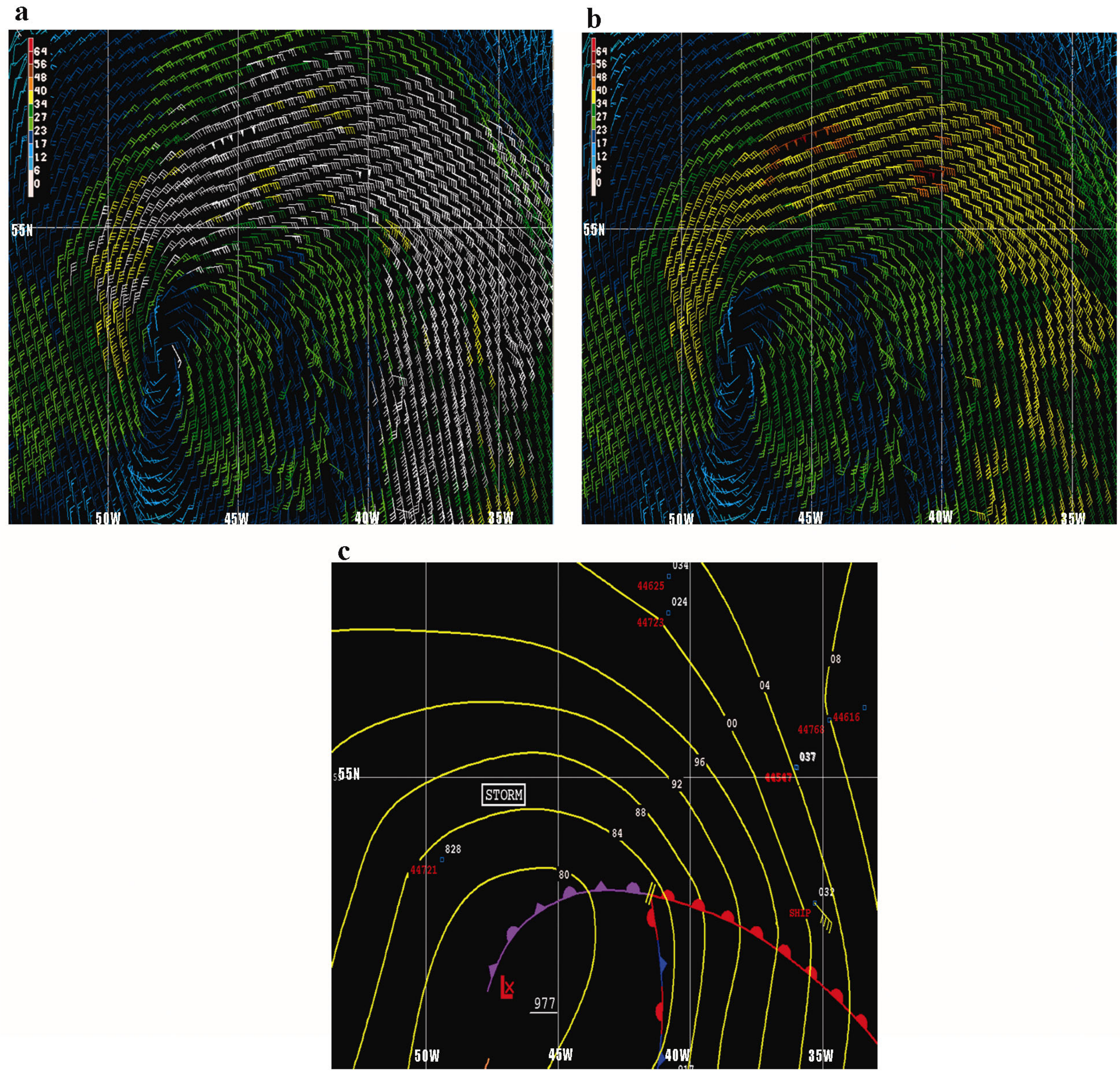

Fig. 9 QuikSCAT winds as in Fig.7 (a) except for 0800 UTC 04 November 2004 centered on 54ºN, 43ºW. The rain flag is turned on in (a) with white wind barbs showing possible rain contamination. In (b) the rain-flag is turned off. Surface analysis for 0600 UTC 04 November 2004 is shown in (c) using the convention described in Fig. 7.

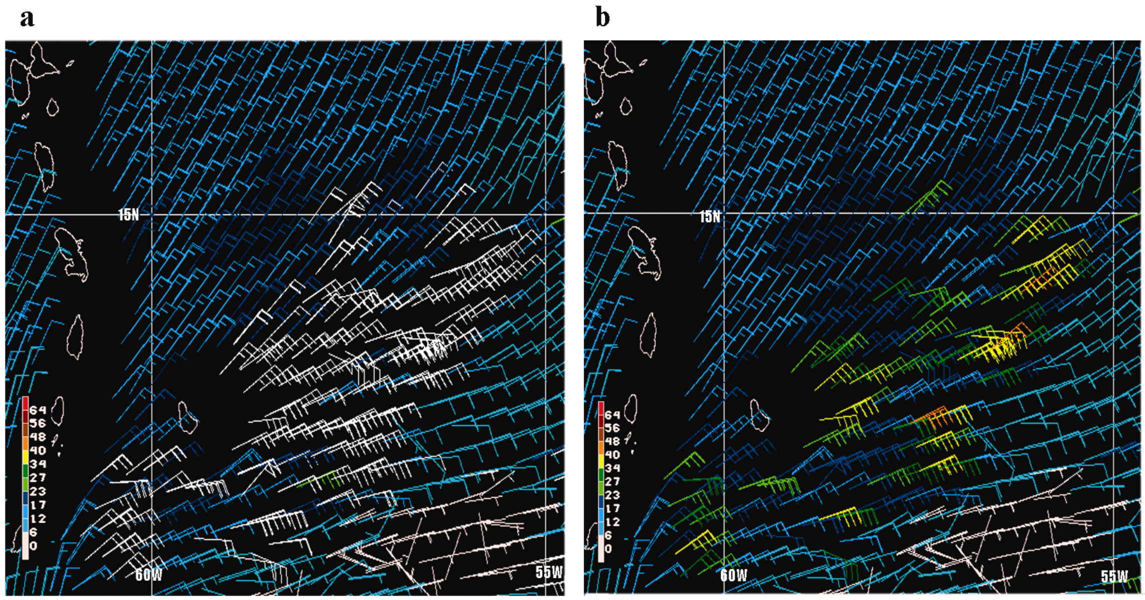

Fig. 10: QuikSCAT winds centered on 13ºN, 58ºW from 0934 UTC 01 December 2004. In (a) the rain flag is turned on. Potentially contaminated winds are shown in white. In (b) the rain flag is turned off.

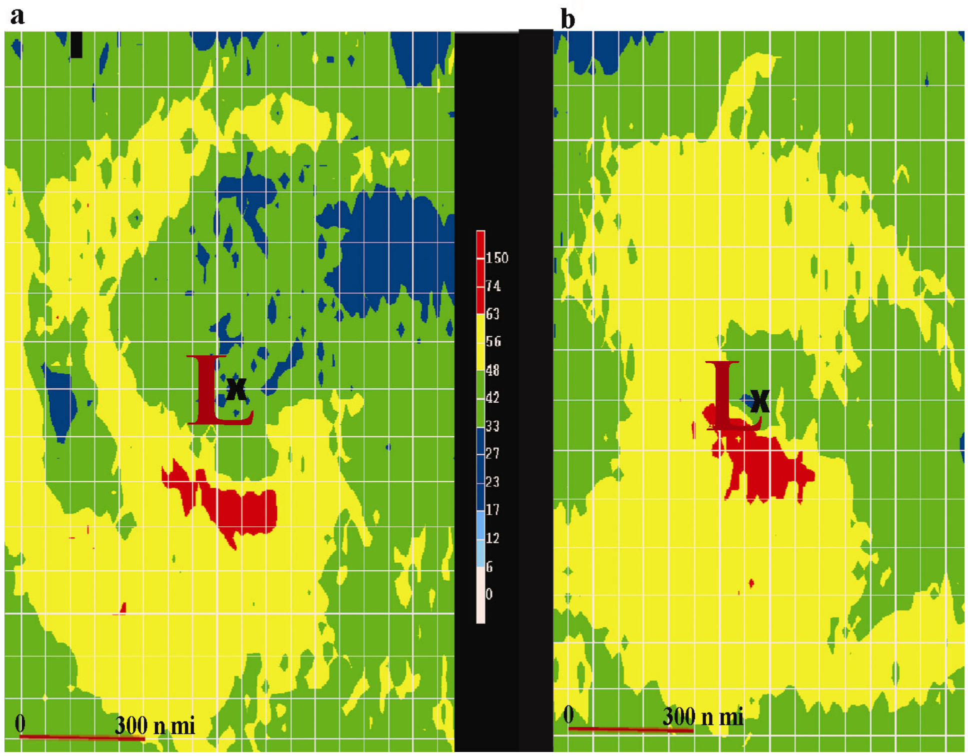

Fig. 11: Composite of maximum winds observed by QuikSCAT for open ocean HF cyclones for the months of October-March 2001-03. Composites are cyclone center relative and were made from (a) 11 North Pacific cyclones and (b) 6 North Atlantic cyclones. Wind speed (kt) is shown by filled contours according to the color bar in the middle of the figure. The red areas indicate maximum winds of HF intensity (in excess of 63 kt (32.7m s^{-1}) Latitude and longitude are in 1 degree intervals. A distance scale is shown in the lower left of each figure as a reference.

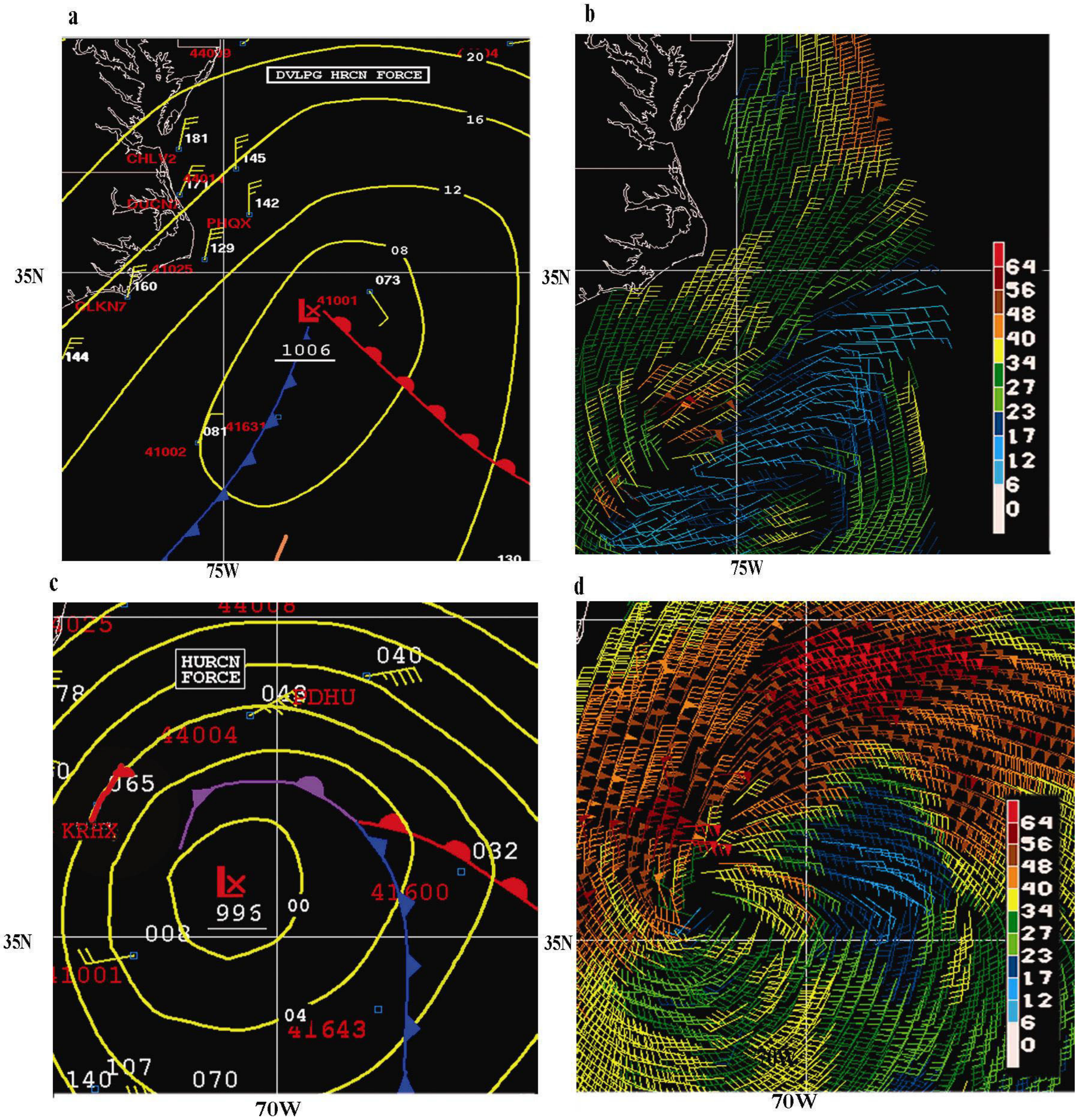

Fig. 12: N-AWIPS display of: (a) OPC Surface analysis for 1200 UTC 10 March 2004. Isobars are drawn in yellow in 4 hPa intervals. Low pressure centers indicated by a red Lx. Fronts are depicted with standard symbols. Ship observations are plotted with a truncated station model showing sea level pressure wind speed and observing ship radio call sign. Winds are plotted in barbs in knots. Wind warning areas are depicted with a text box in the appropriate location. (b) QuikSCAT winds for 1059 UTC 10 March 2004, (c) Surface analysis for 0000 UTC 11 March and (d) as in (b) except for 2300UTC 10 March 2004.

a b

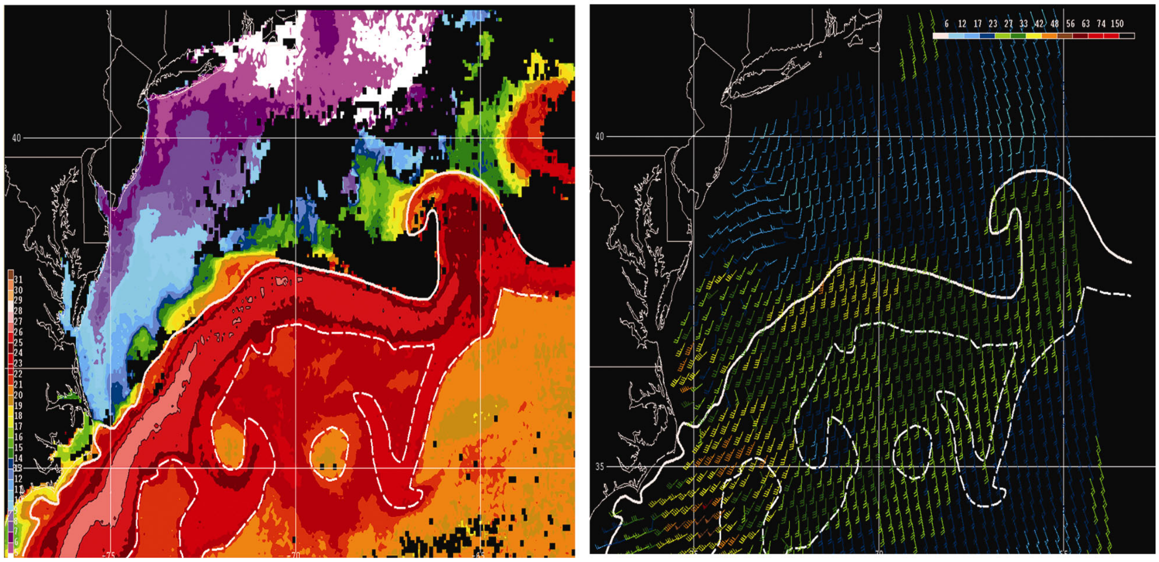

Fig. 13: (a) 3-day SST composite from GOES satellite data for 21 March 2003. Sea Surface Temperature in ºC is shown in color according to the color bar to the left of the figure. (b) Same as 7(a) except for 1022 UTC 21 March 2003. In (a) and (b) the north wall of the Gulf Stream is identified with a solid white line and the south wall with a dashed white line.

TABLE 1. The percent increase in the total number of wind warnings placed on the OPC Surface Analysis using QuikSCAT

	Study #1 Fall 2002 Nov 15–Dec 15	Study #2 Spring 2003 May 15–Jun 15	Study #3 Fall 2003 Nov 15–Dec 15	Study #4 Winter2004 Feb 15-Mar 15
Atlantic	30	7	5	10
Pacific	22	5	4	10

TABLE 2. The number of HF Extratropical Cyclones detected by OPC forecasters using QuikSCAT

Period of Study	Atlantic	Pacific
2001 – 2002	22	15
2002 – 2003	23	22
2003 – 2004	15	22